

Relation Between the Thickness of Stellar Disks and the Relative Mass of Dark Halo in Galaxies

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Abstract

We consider a thickness of stellar disks of late-type galaxies by analyzing the R and K_s band photometric profiles for two independent samples of edge-on galaxies. The main goal is to verify a hypothesis that a thickness of old stellar disks is related to the relative masses of the spherical and disk components of galaxies. We confirm that the radial-to-vertical scale length ratio for galactic disks increases (the disks become thinner) with the increasing of total mass-to-light ratio of the galaxies, which characterize the contribution of dark halo to the total mass, and with the decreasing of central deprojected disk brightness (surface density). Our results are in good agreement with numerical models of collisionless disks evolved from subcritical velocity dispersion state to a marginally stable equilibrium state. This suggests that in most galaxies the vertical stellar velocity dispersion, which determine the equilibrium disk thickness, is close to the minimum value, that ensures disk stability. The thinnest edge-on disks appear to be low brightness galaxies (after deprojection) in which a dark halo mass far exceeds a mass of the stellar disk.

Key words: galaxy structure, galactic dynamics, edge-on galaxies.

INTRODUCTION

Galaxy disks are complex structural components that include the bulk of the stellar mass in most of the spiral galaxies. Their masses and internal structure are crucial factors that determine all large-scale active processes in galaxies, such as propagation of density waves, star formation, and the associated phenomena.

As a rule, the brightness (and, consequently, the surface density) of disks at large galactocentric distances R decreases with increasing R following the exponential law with a radial scale length h of the order of several kpc. Another geometrical parameter of a stellar disk – its thickness – can be characterized by vertical scale length z_0 . In an isothermal disk the decrease of density with the distance from the galactic plane can be described by the simple law:

$$\rho(z) = \rho_0 \operatorname{sech}^2(z/z_0), \quad (1)$$

although some other alternative approximations are possible such as exponential or $\operatorname{sech}(z)$ -model of brightness decrease (de Grijs and van der Kruit 1996).

The thickness z_0 , or the vertical disk scale height, is primarily determined by the local disk density and stellar velocity dispersion. However, as we can see in our own Galaxy, young and old stars have different velocity dispersions resulting in a rather complex vertical disk structure. Actually, since the bulk of the disk mass in spiral galaxies consists of stars that are several billion years old, hereafter we assign the

photometrically determined thickness to the old stellar disk. Note that the insignificant color gradients in edge-on galaxies in the direction perpendicular to the disk plane beyond the narrow dust lane along the major axis (see de Grijs 1998 and references therein) are indicative of a rather homogeneous stellar content of old disks.

In contrast to radial scale length h , the disk thickness can be measured directly only in galaxies where disks are seen edge-on. The relative disk thickness can be characterized, to a first approximation, by the outer isophotal axial ratios b/a of these galaxies, although inferring the vertical-to-horizontal scale length ratio z_0/h from photometric data requires modeling the 3D luminosity distribution of the disk (to make corrections for projection effect).

The observed brightness distribution $\mu(r, z)$ (determined neglecting absorption) in a finite-thickness isothermal disk seen edge-on is related to the parameters h and z_0 via modified Bessel's functions of the first kind, $K_1(r/h)$ (van der Kruit and Searle 1981a):

$$\mu(r, z) = \mu(0, 0) \operatorname{sech}^2 \left(\frac{z}{z_0} \right) \frac{r}{h} K_1 \left(\frac{r}{h} \right), \quad (2)$$

where r and z are the sky-plane coordinates. Given relation (2), z_0 and h can be determined from vertical and major-axis photometric cross sections, respectively. At the peripheral regions of galaxies of great importance may be such parameter as the so-called disk break or cutoff radius, R_c , beyond which the decrease of the disk brightness is described by a shorter exponential scale length than at smaller galactocentric distances. According to different estimates, R_c is typically equal to 3–5 h (see de Grijs et al. 2001; de Grijs and van der Kruit 1996 and references therein).

Indirect estimates of z_0 could be obtained if the stellar velocity dispersion of the old disk population were known. However, such estimates require certain assumptions about the surface density or integrated mass of the exponential disk (Bottenga 1993). The reverse is also true: given the disk thickness, velocity dispersion measurements make it possible to estimate the local surface brightness of the disk and, consequently, its total mass.

The observations of edge-on galaxies showed that the disk thickness varies over a wide range from one galaxy to another, and the apparent axial ratio can be as high as 10–20 for the thinnest disks (Kudrya et al. 1994; Karachentsev et al. 1997). What determines the relative disk thickness remains an open question. It appears to correlate with morphological type, although the latter is determined rather uncertainly for edge-on galaxies – it is inferred not from the shape of spirals but only from the relative size and luminosity of the bulge. The disks of late-type galaxies (Sc–Sd) are, on the average, "thinner" than those of early-type objects (Karachentsev et al. 1997; de Grijs 1998; Ma et al. 1997, 1999). According to de Grijs (1998), the h/z_0 ratio in his sample of edge-on galaxies varies from 1.5–2 for early-type spirals to 3–8 for Sc–Sd galaxies. However, the relative disk thickness does not show any direct correlation with the rotation velocity or luminosity. To illustrate these conclusions, in Fig. 1 we compare the (B -band) a/b ratio according to the Flat Galaxy Catalog (RFGC) (Karachentsev et al. 1999) with the known HI line width (W_{50}), which is approximately equal to twice the maximum velocity V of disk rotation, and with absolute magnitude, M_B (both parameters adopted from LEDA catalog).

It can be expected, however, from the most general considerations that the relative thickness of the equilibrium disk (at least its minimum possible value) must reflect its kinematic characteristics. The disk thickness at a given R is indeed determined by its local surface density and local dispersion C_z of stellar velocities in the direction

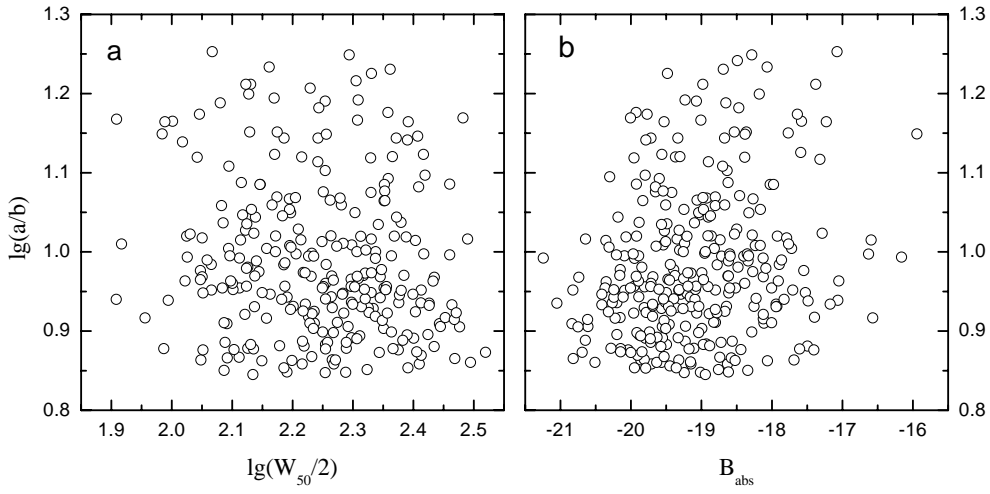


Figure 1: Diagrams illustrating the absence of correlation between the observed axial ratio a/b and the HI line halfwidth, $W_{50}/2$ (a) or absolute magnitude B_{abs} (b) for 340 galaxies from RFGC catalog (Karachentsev et al. 1999).

perpendicular to the disk plane. On the other hand, C_z and radial dispersion C_r are interrelated quantities¹ with the minimum C_r determined by the condition of local gravitational stability of the disk. Zasov et al. (1991) argued that if the radial dispersion C_r of stellar velocities in an old stellar disk is close or proportional to the critical threshold for gravitational (Jeans) instability of the rotating disk, and velocity dispersion C_z along the z -coordinate is proportional to C_r , then the relative disk thickness should increase with decreasing relative mass of the galactic halo.

Indeed, to a first approximation (neglecting the z -component of the acceleration due to the spherical component of the galaxy), $z_0 \approx C_z^2/\pi G\sigma$ (here σ is the disk surface density). Let radial velocity dispersion be equal to $C_r = Q \times 3.36G\sigma/\kappa$, where $\kappa \sim V/R$ is the epicyclic frequency and the Toomre parameter $Q = 1$ corresponds to a thin uniform disk that is marginally stable (in Toomre's sense) to radial perturbations. In general case, Q is a function of radial distance R . Beyond the central bulge-dominated region it varies slowly with R gradually increasing toward the periphery (Bottema 1993). However numerical models of marginally stable disks show that parameter Q remains almost constant over a wide R interval beyond the central region and its value ($Q \approx 1.2 - 1.5$ between 1 and 2 radial scalelengths h) depends only slightly on the mass of the spherical and disk components of a galaxy or the shape of its rotation curve (Khoperskov et al. 2002). Using simplified relationships for z_0 and C_r given above, and taking C_z/C_r and $Q(R) \approx \text{const}$, one may obtain that the vertical-to-radial disk scale length ratio can be easily expressed in terms of other parameters ratios:

$$\frac{z_0}{h} \sim \frac{C_z^2}{\sigma h} \sim \frac{\sigma}{h\kappa^2} \sim \frac{\sigma h^2}{V^2 h} \sim \frac{M_d}{M_t}. \quad (3)$$

Here $M_d \sim \sigma h^2$ and $M_t \sim V^2 h$ are the mass of a disk and the total mass of a galaxy, respectively, within the fixed radius (in the units of h). The thinnest galaxies can

¹According to Gerssen et al. (2000), direct estimates obtained for several galaxies yield $C_z/C_r \approx 0.5 - 0.8$; within approximately the same interval (0.35–0.8) fall the ratios obtained by numerical simulation of the dynamical evolution of initially "cold" collisionless disks (Mikhailova et al. 2001). The condition of stability against bending perturbations for collisionless disk yields $C_z/C_r \approx 0.37$ (Polyachenko and Shukhman 1977)

therefore be expected to be those with the highest mass fraction of the spherical halo. This conclusion agrees well with the results of the 3D N -body numerical simulations of collisionless disks (Zasov and Morozov 1985; Zasov et al. 1991; Mikhailova et al. 2001).

When applied to real galaxies the situation may be complicated by a different factors which can lead to the increasing the thickness of quasi-equilibrium disks in the process of their long evolution due to slow growth of velocity dispersion (Gerssen et al. 2000; Binney 2000). These factors include the scattering of disk stars during their interaction with giant molecular clouds or globular clusters; interaction of stars with density waves; merging of small satellites, which could cross repeatedly over the disk, star formation in the process of gas accretion onto the disk, which has not yet reached equilibrium, and gravitational perturbations due to neighboring galaxies. The latter effect shows up conspicuously in the fact that the relative thickness of disks in interacting systems is about twice larger than in galaxies without close neighbors (Reshetnikov and Combes 1997).

Note that the efficiency of all the processes mentioned above should be different at different galactocentric distances, whereas photometric measurements of edge-on galaxies imply that disk thickness varies only slightly with radius (van der Kruit and Searle 1981a, b; Barnaby and Thronson 1992). (Note however, that some galaxies appear not to obey this rule – see de Grijs and Peletier 1997). The conclusion about the disk thickness remaining constant over a wide interval of galactocentric distances also follows from numerical N -body simulations of the dynamical evolution of initially cold (along the z -coordinate) collisionless disks (Mikhailova et al. 2001).

To clarify the processes that determine the vertical scale height of a stellar disk, it is worth verifying whether the relative thickness of disks seen edge-on correlates with the dark halo mass, and this is just the aim of this work.

GALAXY SAMPLES USED

We chose the galaxies satisfying the condition $a/b \geq 7$ in B band, which is the underlying criterion of the Flat Galaxy Catalog (RFGC, Karachentsev et al. 1999). The objects obeying this criterion are mostly Sc–Sd galaxies ($\sim 75\%$). These are disk-dominated galaxies with the small bulge contribution to the integrated luminosity (although in some cases the bulge presence is clearly seen in central regions), making it easier to determine their vertical and radial scale lengths and the total disk luminosities.

In this work we use two samples of edge-on galaxies. The first sample (below we will refer to it as BTA sample) includes 121 late-type galaxies of Karachentsev et al.’ Catalog. For these galaxies R -band surface CCD photometry was performed at BTA telescope (Karachentsev et al. 1992). We excluded from the initial sample the objects with uncertain shapes of their outer isophotes and those with isophotal asymmetry in the inner region, which might indicate that the disk inclination differs appreciably from 90° . Nearby galaxies ($V < 750 \text{ km/s}$), Virgo members, and galaxies with large galactic extinction ($A_R > 0.5$) were also excluded. Our final analysis was based on the final sample of 51 galaxies.

Karachentsev et al. (1992) gave the estimates of R -band axial ratios a/b , angular sizes of the semi-major axes of the 23 and $24^m/\text{arcsec}^2$ isophotes parallel with the corresponding isophotal magnitudes, and photometric profiles of the observed galaxies.

We estimated the radial scale length h by fitting the photometric major-axis profile

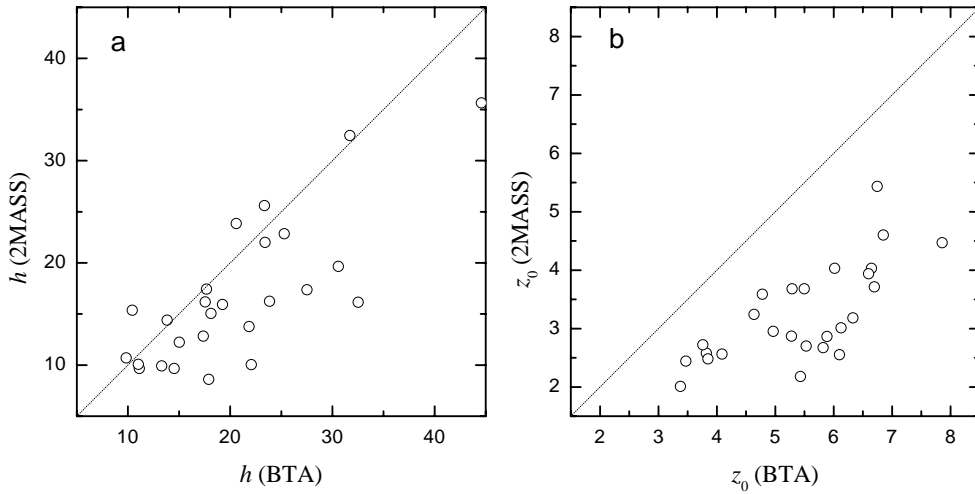


Figure 2: A comparison of radial (a) and vertical (b) disk scale lengths estimations obtained by the different methods in different color bands (BTA – R band; 2MASS – K_s band) for the galaxies common for both samples.

to a function implied by relation (2) at $z_0 = 0$. Given h , the vertical scale height z_0 can be determined by measuring the semi-major (a) and semi-minor (b) axes of a certain isophote of the galaxy (sufficiently far from the center to minimize bulge effects) and using relation (2). The latter implies for the points lying along the major ($a, 0$) and minor ($0, b$) axes:

$$\text{sech}^2\left(\frac{b}{z_0}\right) = \frac{a}{h} K_1\left(\frac{a}{h}\right). \quad (4)$$

Unfortunately, the available photometric data were insufficient to allow a more refined approach making use of the entire pattern of the two-dimensional brightness distribution of a galaxy. We found the galaxies of our sample to have median isophotal major axis to the radial disk scale length ratios, a/h , of 2.9 and 3.7 for the isophotes $23^m/\text{arcsec}^2$ and $24^m/\text{arcsec}^2$, respectively.

As a second sample we analyzed 60 RFGC galaxies chosen for their largest angular size, whose vertical (z_0) and radial (h) disk scale lengths could be determined in a more rigorous way – by modeling photometric cross sections along and across the major axis of the galaxy. For this purpose we used the 2MASS survey K_s -band near-infrared images available from NASA Extragalactic Database (NED). A detailed description of the procedure we used to determine the photometric parameters is given by Bizyaev and Mitronova (2002). The above authors obtained the vertical disk scale heights averaged over 20–30 vertical cross sections. We fitted each profile to a $I = I_0 \text{sech}^2(z/z_0)$ law with allowance for atmospheric blurring.

The radial disk scale lengths were determined from the cross sections parallel to the major axis of the galaxy (but not closer than $\sim 2''$ to avoid the dustiest regions). To minimize bulge effects in the estimated photometric disk parameters z_0 and h , we also excluded the centermost regions in the cases where the isophotal ellipticity decreased centerward (due to the bulge). We treated z_0 and h in equation (2) and the central brightness of the exponential disk as free parameters of the photometric model.

For a comparative analysis of disk scales of two samples we selected 24 brightest ($K_s < 10.5^m$) and relatively distant ($V \gtrsim 750$ km/s) galaxies of the second sample excluding the objects with the strongest galactic extinction $A_K > 0.25$ and probable

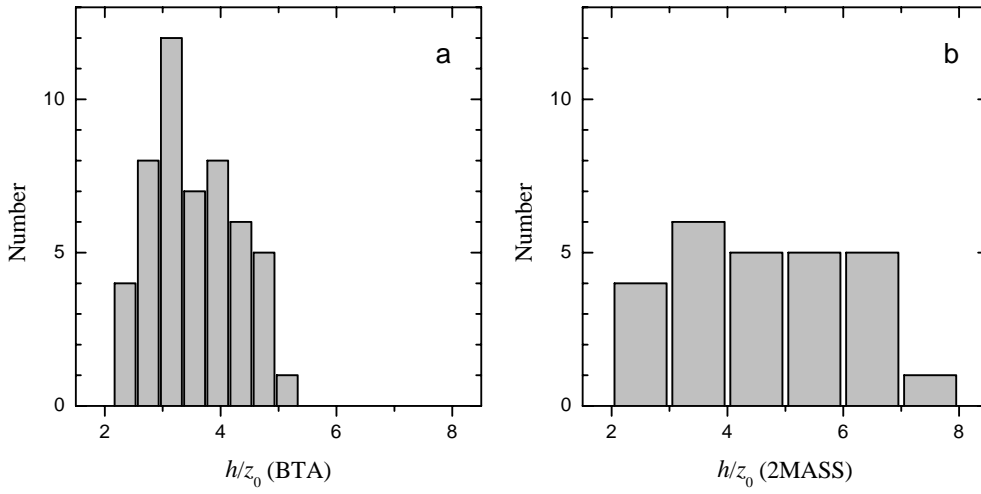


Figure 3: Histogram of the radial-to-vertical disk scale length ratio, h/z_0 , for the galaxy samples considered: (a) – R -band (BTA sample); (b) K_s -band (2MASS sample).

Virgo cluster members.

The first (BTA) sample of galaxies with R -band photometry and the initial sample of galaxies from 2MASS catalog have 28 objects in common. When comparing the two samples we excluded two objects with supposedly non-exponential profiles yielding strongly discrepant scale length estimates obtained in two samples (UGC 542 = RFGC 206 and UGC 7774 = RFGC 2336). In Fig. 2 we compare the independently determined z_0 and h (in arcseconds). The median radial and vertical scale height ratios for both samples are: $h(BTA)/h(2MASS) = 1.21 \pm 0.08$ and $z_0(BTA)/z_0(2MASS) = 1.66 \pm 0.07$, respectively. The relation between the radial scale lengths agrees well with the conclusion of de Grijs (1998) that near-infrared (K) photometric scale lengths are systematically smaller than those measured at shorter wavelengths (by a factor of about ≈ 1.2 and ≈ 1.6 compared to the I - and B -band data, respectively). The scale length ratio z_0/h also decreases as one passes to longer wavelengths (see Fig. 6 of de Grijs (1998)). According to our measurements, the relative thickness of the galaxies of the first sample (R -band) is also greater than that of the second sample (K_s -band) (Fig. 3): the mean (h/z_0) are equal to 3.52 ± 0.1 and 4.93 ± 0.34 for BTA and 2MASS samples, respectively. This effect, however, can be partially due to systematically overestimated z_0 based on BTA data, because the method employed is sensitive to the eventual bulge effects in the computed minor axes of the isophotes used to determine the vertical scale height.

Our photometric measurements showed that the galaxies of the BTA sample have a mean integrated color index of $B - R = 1.06 \pm 0.05$. The mean color indices of the edge-on galaxies common for the two samples are $B - K_s = 3.34 \pm 0.17$ and $R - K_s = 2.24 \pm 0.12$, respectively. These results agree well with the integrated colors of 86 Sc–Sd galaxies oriented almost face-on (de Jong 1996). The absence of strong reddening of edge-on galaxies is no surprise: a dust lane extending along their major axis can strongly decrease the observed luminosity, while having little effect on the color if the optical depth of the dust $\tau \gg 1$.

VERIFICATION OF THE DEPENDENCE OF THE RELATIVE DISK THICKNESS ON THE M/L RATIO OF A GALAXY

If the above mentioned assumption about the decrease of the relative disk thickness with the mass fraction of the spherical component (dark halo) is true,² one should expect the z_0/h ratio to be the lowest in galaxies with high ratio of the integrated mass to the integrated red (infrared) luminosity: the latter is sensitive only slightly to the ongoing star formation and therefore better than the blue light corresponds to the total mass of the stellar population of the disk.

Hereafter we determine the masses of galaxies inside fixed radius of $R_m = 4h$ within which the luminosity (actually, the disk luminosity) was determined from photometric data. Beyond $4h$ less than 10% of the mass of the exponential disk is located – even in the absence of the usually observed steepening of the radial distribution at large R . We assume that the total mass M_t of the galaxy within R_m is approximately equal to $W_H^2 R_m / 4G$, where W_H is the HI line width.³ This simple expression for mass is, strictly speaking, correct for spherically-symmetrical systems, however, this assumption introduces a rather small error. Numerical simulations of galaxies with the measured velocity dispersion of the old disk stellar population imply halo masses exceeding significantly the disk masses within chosen R_m in most of the cases (see for example Zasov et al. 2000; Khoperskov et al. 2001). However, even if the mass of the halo is equal to that of the thick disk within $R_m = 4h$, the above formula overestimates the mass M_t only by $\approx 25\%$.

For the galaxies of the first sample we estimated the galaxy luminosities from the $24^m/\text{arcsec}^2$ isophotal magnitudes extrapolating them if necessary out to R_m based on the radial brightness scale length. The luminosity of galaxies of the second sample were restored from their photometric model parameters. If the relative masses of disk and halo are unknown, the mass of the disk cannot be estimated from the rotation velocity and therefore we infer it from the disk luminosity assuming that $M_d = A(\lambda)L_d \times (M/L)_d$, where $A(\lambda) > 1$ is the factor that allows for internal extinction (which is important for the R band); L_d , the observed disk luminosity, and $(M/L)_d$, the integrated mass-to-luminosity ratio of the stellar population in the chosen photometric band. The total-to-disk mass ratio can therefore be written in the following form:

$$\frac{M_t}{M_d} \approx \frac{W_{50}^2 h}{A(\lambda) G L_d (M/L)_d}. \quad (5)$$

The luminosity underestimation of an edge-on galaxy is difficult to take into account: it can be important even in the infrared. The extinction correction applied to reduce the R -band magnitudes of edge-on galaxies to those of face-on galaxies exceeds, on the average, 1^m (Tully et al. 1998). The estimation of M_d from the observed luminosity is further complicated by the large scatter of coefficient $A(\lambda)$, which, in turn, can depend on the disk mass and thickness. For the second galaxy sample the photometric estimates should be much less affected by dust. The reasons for this are twofold: (1) K_s -band extinction in galaxies resulting from their edge-on orientation does not, on the average, exceed 0.3^m (Tully et al. 1998), and (2) when estimating the scale lengths we excluded the regions close to the Galactic plane, which suffer from the strongest extinction. However, in spite of the simplifying assumptions adopted here both the first and the second galaxy samples exhibit conspicuous relations between

²The samples considered consist mostly of late-type galaxies without massive bulges and therefore the bulk of the mass of the spherical component belongs to the dark halo indeed

³In this work we use the W_{50} width at 50% of the maximum (adopted from LEDA database). However, the choice between W_{20} and W_{50} is of no fundamental importance, because both quantities are close to twice the maximum velocity of gas rotation.

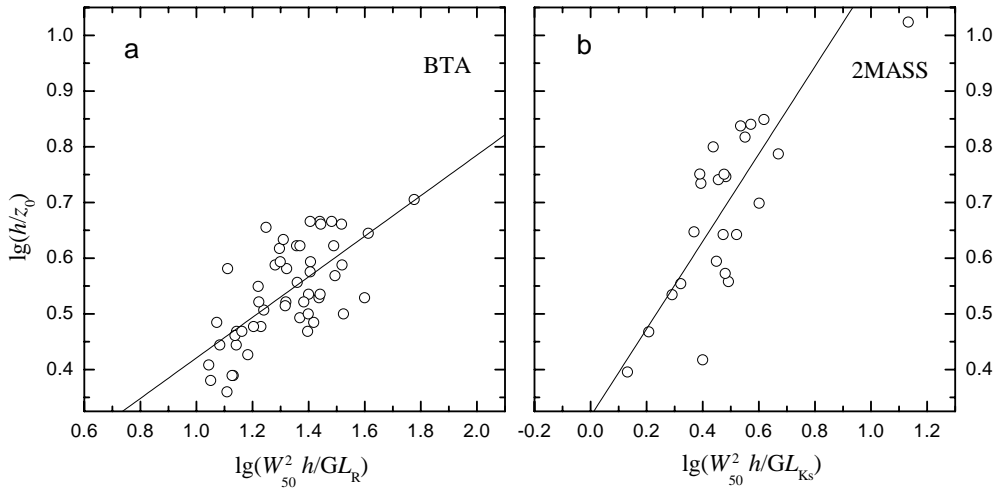


Figure 4: Relation between the photometrically determined radial -to - vertical disk scale length ratio and the quantity $W_{50}^2 h / GL_{(R,K_s)}$, which determines the M_t/L_d ratio within $R = 4h$: (a) R -band (BTA data); (b) K_s -band (2MASS data).

h/z_0 and M_t/L_d (or, to be more precise, a quantity proportional to this ratio) — see Fig. 4 — with the correlation coefficients equal to 0.68 and 0.73, for the first and the second samples respectively. This relation, which corroborates the conclusion that the disk thickness decreases with the relative mass of the spherical component is the main result of this work.

The scatter of data points on the diagrams shown here is due to the errors in the estimates of the parameters used, the difference of A_λ and M/L_d of the stellar populations of individual galaxies, and unaccounted physical factors, which may increase the disk thickness (see Introduction). The differences between the slopes based on two galaxy samples must be real despite the uncertainty of the inferred slope of the relation in Fig. 4(a) (photometric estimates based on 2MASS data are more reliable): the shallower behavior of the R -band relation agrees qualitatively with the fact that thinner galaxies (in the upper part of the diagram) are more extinction affected and thus have their M/L_d overestimated.

DISCUSSION AND CONCLUSIONS

This study may be the first to show that the expected relation exists between the stellar disk thickness and the relative masses of spherical and disk components of a galaxy. Note that the conclusion that marginally stable collisionless disks become thinner with increasing mass fraction of their spherical components (in the absence of external gravitational perturbations) was first reached from N -body numerical simulations of three-dimensional disks in a fixed field of the spherical component starting from an unstable state with low vertical velocity dispersion (Zasov et al. 1991; Mikhailova et al. 2001). As simulations showed, the velocity dispersion C_z increases from the initial values reaching a certain level (decreasing with R) during the time interval equal to several rotation periods at the outer disk edge - evidently as a result of the development of bending perturbations. Eventually the disk becomes marginally stable against both perturbations in its plane and the bending perturbations. Here we refer to Khoperskov et al. (2001, 2002) for a detailed description of numerical simulations.

Figure 5, taken from the paper by Mikhailova et al, 2001 (their Fig. 2) compares

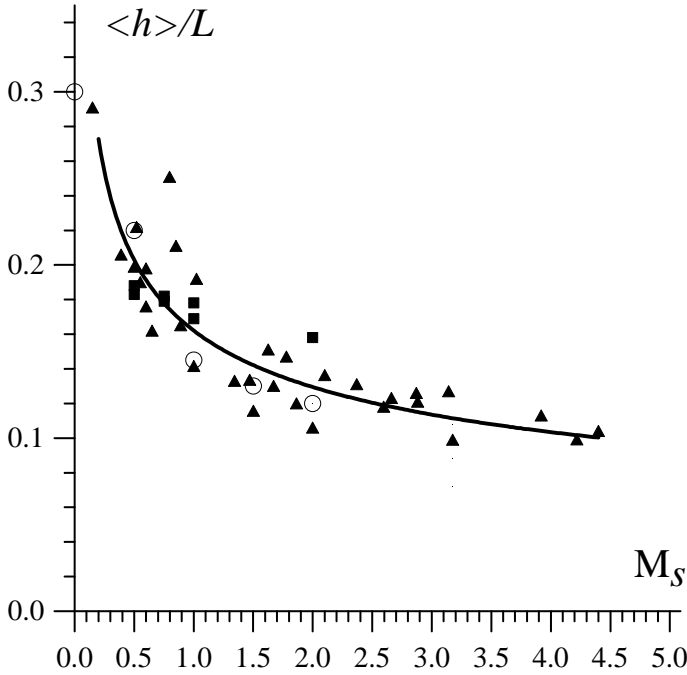


Figure 5: Relation between the rms distance $\langle h \rangle$ of points from the disk plane expressed in the units of the radial disk scale length and the halo to disk mass ratio, M_s , obtained from N -body numerical simulations of galaxies with marginally stable disks. The figure is adopted from Mikhailova et al. (2001, Fig. 2). In our notations $\langle h \rangle/L \approx z_0/h$.

the relative disk thickness and $M_s = (M_t - M_d)/M_d$ – the spherical-to-disk mass ratio – based on the results obtained by constructing numerical models for galaxies with different component masses and different shapes of rotation curves corresponding to those actually observed in real galaxies.

To compare the observed and model relations shown in Figs. 4 and 5, one must convert disk luminosities into disk masses. Assuming, like we did in the previous section, that $W_{50}^2 h/G$ determines the total mass of the galaxy within $R_m = 4h$, we can write the quantity M_s laid off along the horizontal axis in Fig. 5 as:

$$M_s = \frac{W_{50}^2 h}{G \times M_d} - 1, \quad (6)$$

It follows from this equation that:

$$\frac{W_{50}^2 h}{G \times L_d} = (M_s + 1)(M/L)_d, \quad (7)$$

where $(M/L)_d$ is the disk mass-to-luminosity ratio for the chosen spectral interval.

Figure 6 shows in a logarithmic scale the diagram given in Fig. 4 with the superimposed curve from Fig. 5 computed in accordance with equation (7) for three mass-to- K_s -band luminosity ratios ($M/L_d = 1, 2$, and 3).

Evolutionary models yield for the stellar population of cosmological-age galaxies a mass-to-luminosity ratio of $(M/L)_{\text{model}} \approx 1$ for the photometric K band, which is close to K_s (Bell and de Jong 2001). This ratio remains somewhat uncertain due to the lack of data about the low-mass end of the stellar mass function. All galaxies are actually situated in the domain between the adopted ratios, which are quite reasonable for an old stellar population. It shows that models of marginally stable disks agree

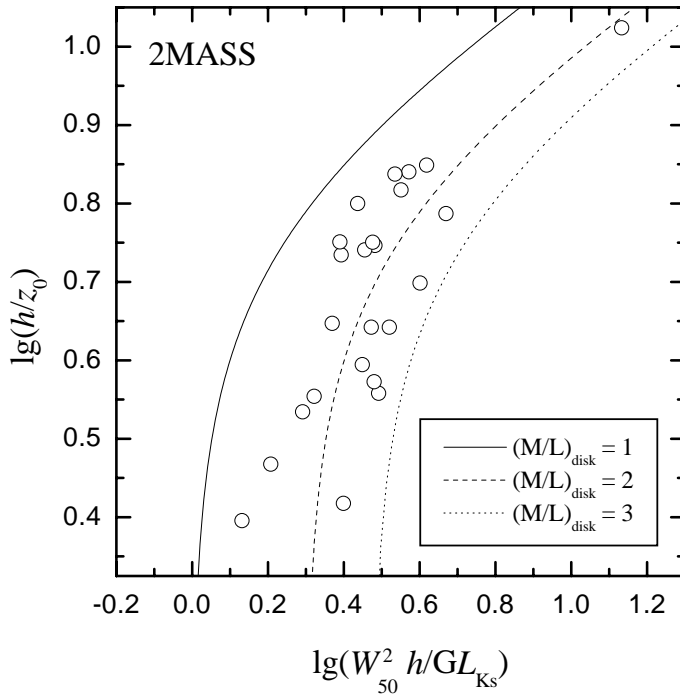


Figure 6: The same diagram as in Fig. 4b with superimposed collisionless-disk relation inferred from numerical simulations (the curve in Fig. 5) recalculated for three disk mass-to-luminosity ratios (in solar units): $(M/L)_d = 1, 2$, and 3 .

well with observations. This leads us to conclude that for most of the galaxies the mechanisms of additional disk heating (scattering by massive clouds, tidal perturbation of the disk) are not crucial for the formation of the vertical disk structure. Hence the approximately constant disk thickness along the radius may be considered as a result of the two opposite tendencies influencing the disk thickness: — the radial decrease of surface disk density and the decrease of the velocity dispersion at which the disk reaches stable equilibrium — both factors cancel almost exactly each other.

Figure 7 compares the relative disk thickness with central surface brightness (in magnitudes) reduced to face-on position using model R - and K_s -band brightness distributions. The correlation between these parameters is even more conspicuous than that between z_0/h and $(M/L)_t$, although the very existence of such a relation is nothing unexpected: "normal" and low surface brightness galaxies were already shown to exhibit a close relation between S_0 and integrated ratio $(M/L)_t$, which characterizes the dark halo mass fraction (MacGaugh and de Block 1998). The lower the central surface brightness (and, consequently, the surface density), the higher the dark halo mass fraction within the chosen $R = R_m$. The correlation between these two quantities implies, in particular, the existence of a single linear (in the logarithmic terms) Tully–Fisher relation (luminosity or mass of the disk – rotation velocity) for galaxies with different surface brightness S_0 (MacGaugh and de Block 1998).

This relation manifests itself most conspicuously in the diagram shown by Bizyaev and Mitronova (2002), which is based on an analysis of a 153 galaxy sample from the 2MASS survey. This relation appears to be more scattered at longer-wavelength bands (as is evident from a comparison of diagrams a and b in Fig. 7); Bizyaev and Kaisin (in preparation) and Bizyaev (2000) came to the same conclusion based on R and I -band photometry, respectively. The same dependence in the B -band is the least conspicuous (see Fig. 9 in the paper of de Grijs (1998)). The differences between the correlation

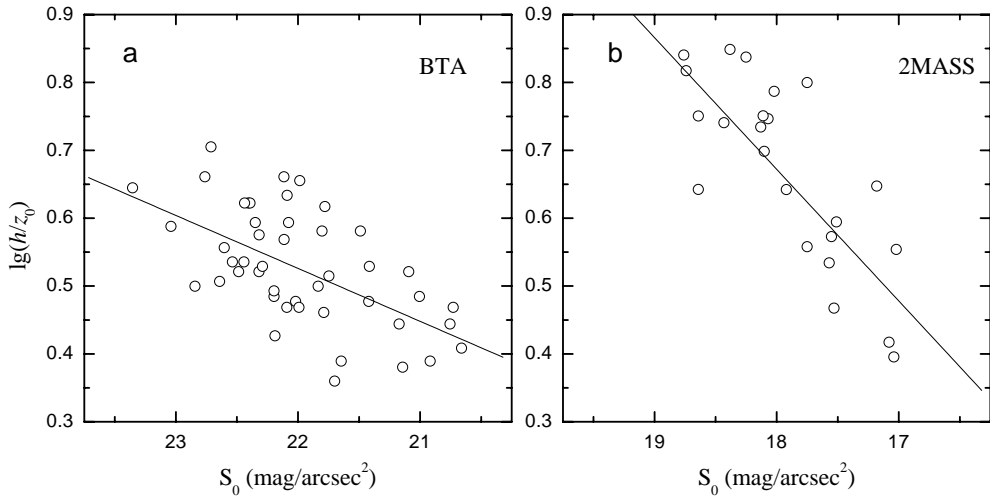


Figure 7: Radial-to-vertical disk scale length ratio as a function of deprojected central disk brightness in magnitudes in the (a) R - and (b) K_s -band.

coefficients and slopes of relations shown in Fig. 7 are evidently due to selective internal extinction, which is strongest in galaxies with thin disks and becomes more important at shorter wavelengths. Indeed, the underestimated brightness (or overestimated S_0 , expressed in magnitudes) for galaxies with "thin" disks result in an underestimated slope of the relation in Fig. 7. It is not surprising that the relation is more conspicuous in the K_s band (Fig. 7b) where the internal extinction amounts only to several tenths of a magnitude.

Thus the relations obtained lead us to conclude that the thinnest edge-on galaxies are to be (after deprojection to a face-on orientation) low surface brightness spirals whose observed brightness is enhanced by projection effect and whose dark-halo mass exceeds significantly the mass of the disk.

Note, however, that not all disk galaxies appear to obey the "dark-halo mass – disk thickness" relation. Relatively thick disks are observed not only in interacting systems (Reshetnikov and Combes, 1997) but also in comparatively low luminous Irr galaxies, for which some authors pointed out a deficit of systems with strong apparent flattening (Hodge and Hitchcock 1966; Thuan and Seitzer 1979; van den Bergh 1988), and all this in spite of the fact that the dark halo mass fraction in low luminosity galaxies is, on the average, higher than in galaxies with high luminosity (Persik and Salucci 1996 ; Ashman 1992; Cote et al. 2000). Relatively thick disks observed in Irr-galaxies may be a result of, among other things, a certain threshold level of stellar velocity dispersion, which cannot be lower than the velocity dispersion of gaseous clouds (usually ≈ 10 km/s). Unfortunately, the strong contribution of young stars to the disk luminosity in Irr-galaxies and their nonuniform distribution within the galaxy complicate the vertical photometric disk structure and increase the uncertainty of the photometric tilt estimates compared to what we have in the case of spiral galaxies, thus preventing any direct comparison of the stellar disk thickness of these two types of objects.

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